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Measurement of the Branching Fractions for $J/\psi \to \ell^+\ell^-$

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Abstract

We present measurements of the branching fractions for $J/\psi \to e^+e^-$ and $\mu^+\mu^-$ using 3M $\psi(2S)$ decays collected with the CLEO detector operating at the CESR e^+e^- collider. We obtain $\mathcal{B}(J/\psi \to e^+e^-) = (5.945 \pm 0.067 \pm 0.042)\%$ and $\mathcal{B}(J/\psi \to \mu^+\mu^-) = (5.960 \pm 0.065 \pm 0.050)\%$, leading to an average of $\mathcal{B}(J/\psi \to \ell^+\ell^-) = (5.953 \pm 0.056 \pm 0.042)\%$ and a ratio of $\mathcal{B}(J/\psi \to e^+e^-)/\mathcal{B}(J/\psi \to \mu^+\mu^-) = (99.7 \pm 1.2 \pm 0.6)\%$, all consistent with, but more precise than, previous measurements.

The J/ψ meson is often experimentally identified through its two largest and cleanest exclusive decay modes, $J/\psi \to e^+e^-$ or $\mu^+\mu^-$, and hence the corresponding branching fractions are of general interest. The process is thought to occur through annihilation of the $c\bar{c}$ pair into a virtual photon which then materializes as a lepton pair, thereby relating to the $c\bar{c}$ wave function overlap at the origin and playing a direct role in potential models [1]. The dilepton branching fraction serves as an ingredient in the measurement [2] of the J/ψ dileptonic and total widths (Γ_{ee} and $\Gamma_{\rm tot}$). It also acts as a normalization in the comparison of $\psi(2S)$ and J/ψ exclusive final state production of light hadrons; the assumption is that the underlying hard reaction, namely annihilation of the heavy quark pair, is the same in both cases.

The current experimental status is that both lepton pair species have been measured to be equal in production rate, as expected from lepton universality (in combination with a negligible correction for phase space), at branching fractions of $\sim 5.9\%$. A relative precision of 1.7% on each of $\mathcal{B}(J/\psi \to e^+e^-)$ and $\mathcal{B}(J/\psi \to \mu^+\mu^-)$ has been achieved through an average [3] over measurements, which is dominated by a result from BES [4]: $\mathcal{B}(J/\psi \to e^+e^-) = (5.90 \pm 0.05 \pm 0.10)\%$, $\mathcal{B}(J/\psi \to \mu^+\mu^-) = (5.84 \pm 0.06 \pm 0.10)\%$, and $\mathcal{B}(J/\psi \to \ell^+\ell^-) = (5.87 \pm 0.04 \pm 0.09)\%$. The current precision of $\mathcal{B}(J/\psi \to \ell^+\ell^-)$ is a significant contributor to the uncertainties on Γ_{ee} and $\Gamma_{\rm tot}$ obtained from measurement of radiative return ($e^+e^- \to \gamma J/\psi$, $J/\psi \to \mu^+\mu^-$) cross sections [2].

In this article we describe measurements of $\mathcal{B}(J/\psi \to e^+e^-)$ and $\mathcal{B}(J/\psi \to \mu^+\mu^-)$ using the decay $\psi(2S) \to \pi^+\pi^- J/\psi$. The experimental procedure is straightforward and consists of determining the ratios of the numbers of exclusive $J/\psi \to \ell^+\ell^-$ decays for $\ell = e$ and μ, $N_{e^+e^-}$ and $N_{\mu^+\mu^-}$, to the number of inclusive $J/\psi \to X$ decays, N_X, where X means all final states. The branching fractions will be calculated as $\mathcal{B}(J/\psi \to \ell^+\ell^-) = (N_{\ell^+\ell^-}/\epsilon_{\ell^+\ell^-})/(N_X/\epsilon_X)$, where $\epsilon_{\ell^+\ell^-}$ and ϵ_X represent the detection probabilities for the exclusive and inclusive events, respectively.

We use e^+e^- collision data at and below the $\psi(2S)$ resonance, $\sqrt{s} = 3.686\,\mathrm{GeV}$ ($\mathcal{L} = 5.86\,\mathrm{pb}^{-1}$) and $\sqrt{s} = 3.670\,\mathrm{GeV}$ ($\mathcal{L} = 20.46\,\mathrm{pb}^{-1}$), collected with the CLEO detector [5] operating at the Cornell Electron Storage Ring (CESR) [6]. The CLEO detector features a solid angle coverage of 93% for charged and neutral particles. The charged particle system operates in a 1.0 T magnetic field along the beam axis and achieves a momentum resolution of $\sim 0.6\%$ at momenta of $1\,\mathrm{GeV}/c$.

Identification of $\pi^+\pi^- J/\psi$ candidates is performed by tagging the dipion pair: two tracks of opposite charge with $m(\pi^+\pi^-) = 400 - 600\,\mathrm{MeV}$, $|\cos\theta| < 0.83$ (where θ is the polar angle of each track with respect to the e^+ direction), and, to avoid tracks which bend back into the tracking detectors before they can enter the calorimeter ('curlers'), a momentum component transverse to the beam axis exceeding $150\,\mathrm{MeV}/c$. The number of $J/\psi \to X$ events is determined from a fit to the distribution of the invariant mass recoiling against the dipion pair, $m(\pi^+\pi^-\text{-recoil})$, in the $\pi^+\pi^- X$ sample after applying this preselection.

To select event samples of $J/\psi \to \ell^+\ell^-$, we demand that candidate events fulfil the following requirements: The lepton pair, consisting of the two highest-momentum tracks in the event, must satisfy the very loose identification criteria of $E/p > 0.85$ for one electron and $E/p > 0.5$ for the other, or $E/p < 0.25$ and $E/p < 0.5$ in case of muons, where E is the measured calorimetric energy deposition of each track and p is its measured momentum. The invariant mass of the track pair must be consistent with that of a J/ψ, with $m(\ell^+\ell^-) = 3.02 - 3.22\,\mathrm{GeV}$. In order to salvage lepton pairs that have radiated photons and would hence fail the J/ψ mass cut, we add bremsstrahlung photon candidates found within a cone of

100 mrad to the track three-vector at the e^+e^- interaction point. We impose loose restrictions on the absolute momentum and energy of the event: $(E_{J/\psi} + E_{\pi^+\pi^-})/\sqrt{s} = 0.95 - 1.05$, $||p_{J/\psi}| - |p_{\pi^+\pi^-}||/\sqrt{s} < 0.07$. We search for the same signature in data taken 15 MeV below the $\psi(2S)$ resonance and find a level of population consistent with the Breit-Wigner tail of the $\psi(2S)$. Backgrounds from other $\psi(2S)$ decays mimicking the desired signature are subtracted, which is a relative reduction of 0.07% for dielectrons (mostly $\psi(2S) \to \eta J/\psi,\ J/\psi \to e^+e^-$) and 0.2% for dimuons (consisting of $\psi(2S) \to \eta J/\psi,\ J/\psi \to \mu^+\mu^-$ at a similar level as electrons, as well as $\psi(2S) \to \pi^+\pi^-$ and to a lesser extent $\psi(2S) \to \rho\pi$). The resulting event yield is $N_{\ell^+\ell^-}$.

The detection probabilities are determined from MC simulation using the `EvtGen` generator [8] and a GEANT-based [9] detector simulation. The dipion invariant mass distribution as produced by `EvtGen` is slightly suppressed at high and low $m(\pi^+\pi^-)$ to better match the data, altering the efficiencies by $< 0.5\%$.

We demonstrate the statistical power of the data sample, its cleanliness, and the excellent agreement observed between data and Monte Carlo (MC) in Figures 1 and 2, where we show the invariant masses of the dipion pair (direct and recoil) and the dilepton pairs, and also the lepton and J/ψ polar angle distributions. Further evidence for the high degree of quantitative understanding of $\psi(2S)$ decays to final states with a J/ψ in CLEO can be found in Ref. [10].

We follow a procedure similar to that employed by BES [4] and Mark III [7] to obtain the raw number of $J/\psi \to X$ decays, in which the $m(\pi^+\pi^-$-recoil) spectrum is fit to obtain the number of J/ψ candidates. Since the dipion emission occurs independently of the subsequent J/ψ decay, the dipion recoil mass shape can be taken from any cleanly determined J/ψ decay. This grants us considerable freedom from the accuracy of MC in modeling the momentum resolution. We use the sum of $J/\psi \to e^+e^-$ and $J/\psi \to \mu^+\mu^-$, which is almost background-free, for the signal shape of the dipion recoil mass distribution. As our MC does not perfectly describe the shape of data, the $\pi^+\pi^- X$ data recoil mass distribution is fit with the $\pi^+\pi^-\ell^+\ell^-$ signal shape from data. The fit, shown in Figure 3, uses a second-order polynomial background shape. The confidence level of the fit is 23%. Increasing the order of the polynomial describing the background does not alter the fitted signal normalization nor substantially improve the fit.

Since the sum of known exclusive J/ψ partial widths is small compared to the total width, a MC sample must be chosen somewhat arbitrarily to represent all J/ψ decays and from which to obtain ϵ_X. We calculate the inclusive $\pi^+\pi^- J/\psi,\ J/\psi \to X$ counting efficiency for a selection of modes with different charged and neutral multiplicities. The efficiencies thus determined are $\sim$40% and vary by only $\sim$2% (relative) from low to high multiplicities, nearly an order of magnitude smaller variation than that reported in [4]. We attribute this effect to the finer segmentation in the CLEO tracking system [5] relative to that of BES [11] and the consequent robustness of track-finding in the presence of many charged particles. The efficiency does exhibit a small dependence not only on the charged multiplicity, but also on the neutral multiplicity. The addition of neutral particles in the J/ψ decay softens the momentum spectrum of the charged tracks, causing some to be lost at low momentum or small polar angles, and also adds to the track multiplicity through photon conversions in the material of the inner detectors. Curlers are also produced more often, which can make pattern recognition more difficult. Even so, such deleterious effects are very small.

Given that the detection efficiency for J/ψ decay products in $\pi^+\pi^- J/\psi$ events depends on the track multiplicity, we let this quantity guide us in the choice of an appropriate

mixture of J/ψ decay modes in MC (a basis set). The measured charged multiplicity, shown in Fig. 4, is obtained from events with $m(\pi^+\pi^-\text{-recoil})$=3.090 − 3.104 GeV after subtracting sideband contributions with $m(\pi^+\pi^-\text{-recoil})$=[3.078−3.085], [3.110−3.117] GeV. We investigate a variety of alternatives for the basis set. The best fit to the J/ψ charged multiplicity distribution is obtained by incorporating three well-measured contributions i, $i = e^+e^-$, $\mu^+\mu^-$, $\rho\pi$, with their branching fractions [3] as fixed weights w_i, and additional contributions with floating normalizations: $\omega\pi^0\pi^0 \to \gamma 3\pi^0$, $\omega\pi^0$, $2\pi^\pm 3\pi^0$, $4\pi^\pm 5\pi^0$, $6\pi^\pm 2\pi^0$, $8\pi^\pm 1\pi^0$. The result of this fit is an effective branching fraction for each of the modes with floating normalization. The only purpose of this basis set is to reproduce the charged multiplicity of the data, thereby permitting an accurate determination of ϵ_X; the basis set is not intended to characterize exclusive J/ψ decays. Substituting for the basis set members of multiplicities 2, 4, or 6 a similar mode with even one more or fewer π^0 results in poorer representations of the data.

The inclusive efficiency ϵ_X is determined by fitting the $m(\pi^+\pi^-\text{-recoil})$ distribution obtained from mixing the MC events in the proportions given by the weights in Table I, using a signal shape from $\pi^+\pi^-\ell^+\ell^-$ MC events. The same value is obtained if, instead of a fit to the weighted MC components, we calculate a weighted average of the individual mode efficiencies.

The resulting raw and efficiency corrected yields are listed in Table II.

The fit result, N_X, has a relative statistical uncertainty of 0.65%, dominated by the statistical uncertainty on the number of events determining the signal input shape. We assign the following additional systematic uncertainties, with the same values for the dimuon and dielectron samples: for dipion charged track multiplicity weighting and choice of basis set, 0.3%, and for yield fit-window variation, 0.5%. The former is set by the variation induced by using other combinations of exclusive J/ψ decays (basis sets) that still closely match the multiplicity distribution of the data; the latter by variations of the window limits as low as 3.04 GeV and as high as 3.15 GeV.

It is to be noted that systematic effects related to soft pion tracking cancel in the ratios. Systematic studies for detection of the lepton pair track candidates follow.

We select $\pi^+\pi^-\ell^\pm(\ell^\mp)$ events by requiring $m(\pi^+\pi^-\text{-recoil})$=3.05-3.15 GeV and only *one* lepton satisfying $|\cos\theta_\ell| < 0.83$ and $p = 1.35 - 1.85\,\text{GeV}/c$, but more strongly identified ($E/p > 0.85$ for electrons, and for muons $E/p < 0.25$ and a penetration of more than three absorption lengths in the CLEO muon detector). Each event must have a missing momentum direction of $|\cos\theta_{\text{miss}}| < 0.75$ and a missing-mass-squared of less than $0.2\,\text{GeV}^2$. In these events, we proceed to search for a second lepton of opposite charge, $E/p > 0.5$ (e) or $E/p < 0.5$ (μ) and momentum $p > 0.8\,\text{GeV}$, that produces a dilepton mass of $m(\ell^+\ell^-) = 3.02 - 3.22\,\text{GeV}$. The fraction of events in which we fail to identify the second lepton is compared between data and MC. The relative failure rate discrepancy between data and MC is $(0.85 \pm 0.13)\%$ for dimuon events and $(0.01 \pm 0.20)\%$ (statistical errors only) for dielectron events. These measured data−MC differences are used to establish yield correction factors (0.995 for muons, 1.000 for electrons) applied to $\epsilon_{\ell^+\ell^-}$ and systematic uncertainties of 0.5% (0.2%) per $\mu^+\mu^-$ (e^+e^-). Effects that can produce such a mismatch between data and MC for either lepton species include track reconstruction systematics and, more importantly, mismodeling of decay radiation, which leads to a loss of events by causing a failure of the invariant mass requirement. The quoted uncertainty includes both.

The remaining source of systematic uncertainty not addressed by the above lepton pair efficiency study is modeling of the E/p requirements, which distinguish muons and electrons

from each other and from hadrons. This uncertainty is determined by varying the value of the E/p cuts around the nominal values, and is found to be 0.1% for both muon and electron pairs.

After including additional relative uncertainties from MC statistics (0.2%) and hadronic event trigger efficiency (0.2%) in quadrature with the above, the total relative systematic error is 0.7% for $\mathcal{B}(J/\psi \to e^+e^-)$ and 0.8% for $\mathcal{B}(J/\psi \to \mu^+\mu^-)$.

Final results are $\mathcal{B}(J/\psi \to e^+e^-) = (5.945 \pm 0.067 \pm 0.042)\%$, $\mathcal{B}(J/\psi \to \mu^+\mu^-) = (5.960 \pm 0.065 \pm 0.050)\%$, and $\mathcal{B}(J/\psi \to e^+e^-)/\mathcal{B}(J/\psi \to \mu^+\mu^-) = (99.7 \pm 1.2 \pm 0.6)\%$. Assuming lepton universality, the average is $\mathcal{B}(J/\psi \to \ell^+\ell^-) = (5.953 \pm 0.056 \pm 0.042)\%$, in which we have accounted for correlations among the errors. These results are consistent with previous measurements, but improve considerably upon precision, constituting the most precise measurements to date. The 1.18% relative (0.070% absolute) uncertainty on $\mathcal{B}(J/\psi \to \ell^+\ell^-)$ is significantly smaller than the previous smallest uncertainty [4], allows improvement in the precision of present and future measurements [2] of Γ_{ee} and Γ_{tot}, and provides an important benchmark and calibration point for potential models [1].

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TABLE I: For different MC $\pi^+\pi^- J/\psi$, $J/\psi \to X$ decays (left column): The weights w_i obtained in the fit to the multiplicity, which are used in the fit extracting ϵ_X, and the relative difference between the efficiencies ϵ_X, obtained using the default w_i, and ϵ_i, employing the dipion recoil mass distribution from each channel alone.

J/ψ decay	w_i (%)	$\epsilon_i/\epsilon_X - 1$ (%)
e^+e^-	5.9	$+0.50 \pm 0.43$
$\mu^+\mu^-$	5.9	$+0.92 \pm 0.43$
$\rho\pi$	2.1	$+0.35 \pm 0.65$
$\gamma 3\pi^0$	1.1	$+1.35 \pm 0.62$
$\omega\pi^0$	19.5	-0.15 ± 0.67
$2\pi^\pm 3\pi^0$	6.4	$+1.24 \pm 0.86$
$4\pi^\pm 5\pi^0$	42.9	$+0.10 \pm 0.67$
$6\pi^\pm 2\pi^0$	14.4	-0.72 ± 0.80
$8\pi^\pm 1\pi^0$	1.8	-0.67 ± 0.75

TABLE II: Summary of $\mathcal{B}(J/\psi \to \ell^+\ell^-)$ results, showing numbers of $\psi(2S) \to \pi^+\pi^-\ell^+\ell^-$ decays, $N_{e^+e^-}$ and $N_{\mu^+\mu^-}$; efficiencies for observing those decays, $\epsilon_{e^+e^-}$ and $\epsilon_{\mu^+\mu^-}$; the corrected number of such decays produced in the data sample; the number of inclusive $\pi^+\pi^- J/\psi$ decays observed in the data sample and extracted from the fit described in the text, N_X; the corresponding efficiency, ϵ_X, the corrected number of inclusive $\pi^+\pi^- J/\psi$ decays produced in the data sample, and relative statistical uncertainties on all quantities.

Quantity	Value	Rel. error (%)
$N_{e^+e^-}$	14830	0.82
$\epsilon_{e^+e^-}$ (%)	24.95	0.24
$N_{e^+e^-}/\epsilon_{e^+e^-}$	59443	0.86
$N_{\mu^+\mu^-}$	16697	0.77
$\epsilon_{\mu^+\mu^-}$ (%)	28.02	0.22
$N_{\mu^+\mu^-}/\epsilon_{\mu^+\mu^-}$	59588	0.81
N_X	395835	0.65
ϵ_X (%)	39.59	0.35
N_X/ϵ_X	999814	0.74

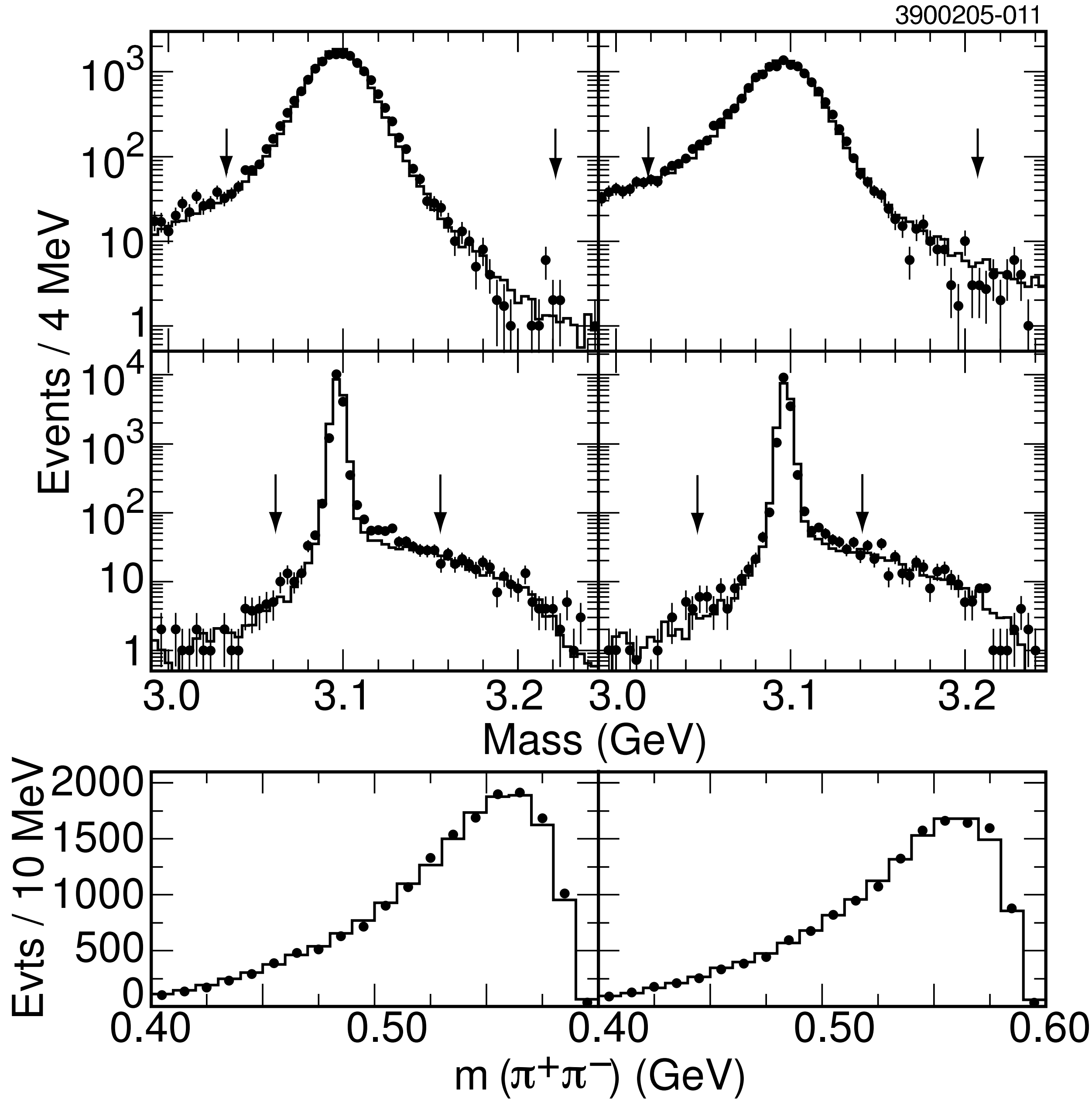

FIG. 1: For $\psi(2S) \to \pi^+\pi^-\ell^+\ell^-$ dimuon (left) and dielectron (right) candidate events in the $\psi(2S)$ data (solid circles), MC simulation of signal (solid histogram), distributions of the dilepton mass (top), the mass recoiling against the $\pi^+\pi^-$ pair (middle), and the dipion invariant mass. The arrows shown in each plot indicate nominal cut values, which are applied for the other plots in the figure.

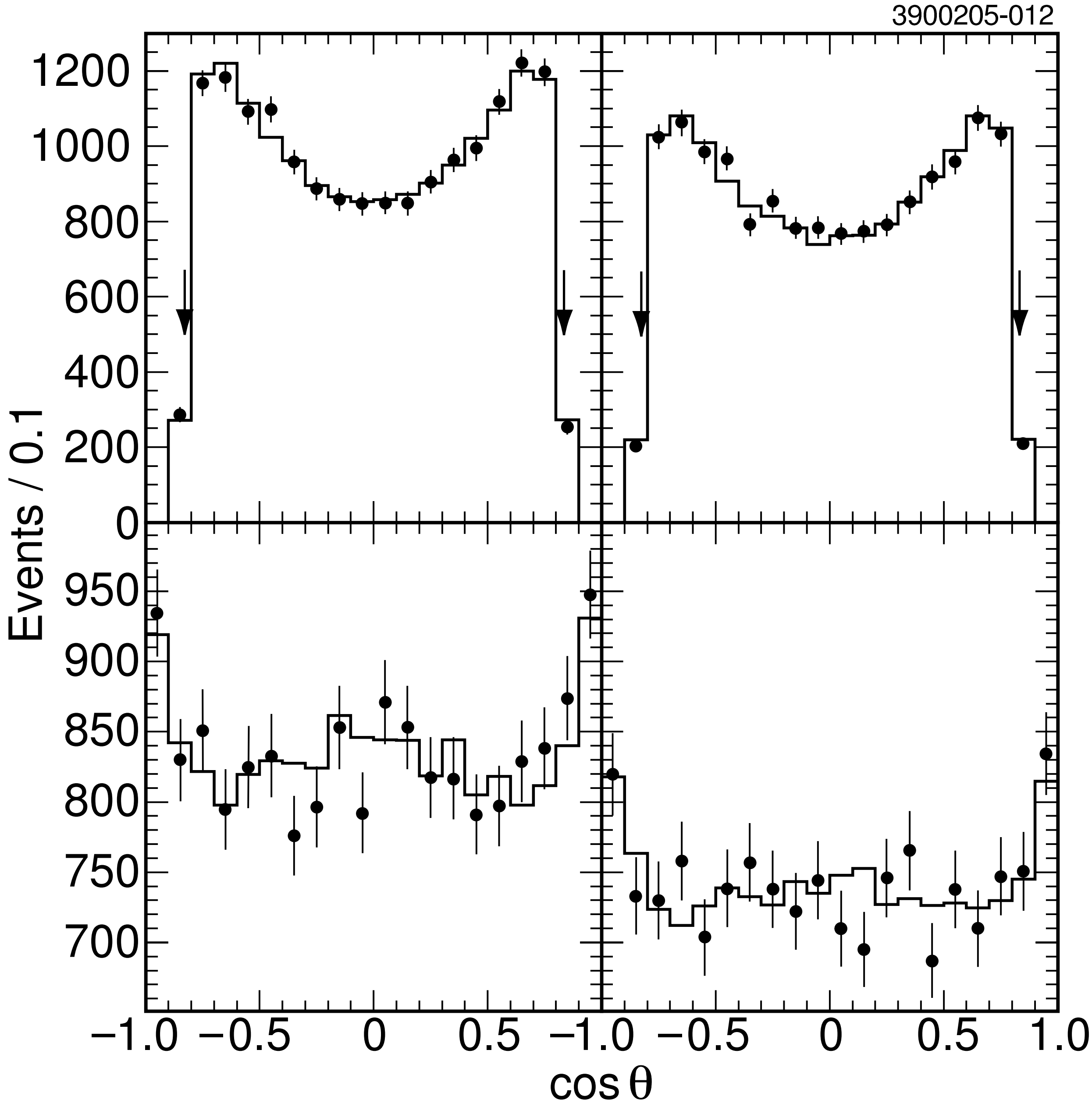

FIG. 2: For $\psi(2S) \to \pi^+\pi^-\ell^+\ell^-$ dimuon (left) and dielectron (right) candidate events in the $\psi(2S)$ data (solid circles) and MC simulation of signal (solid histogram), the polar angles of the positively charged lepton (top) and of the J/ψ (bottom).

FIG. 3: Fit result (solid histogram) of the $\pi^+\pi^-$ recoil mass spectrum in data (solid circles) as described in the text. The dashed curve represents the background shape.

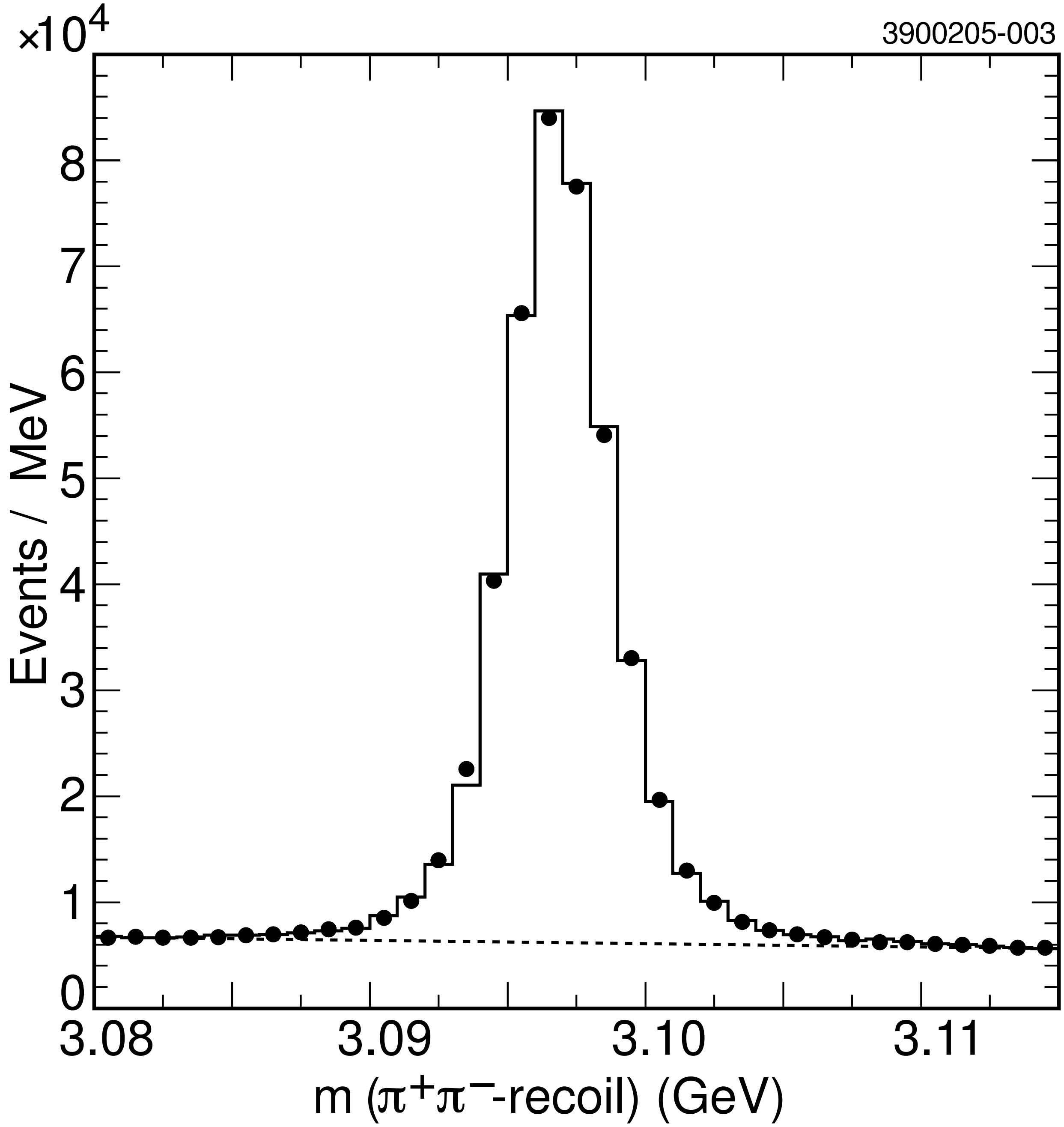

FIG. 4: Track multiplicity distribution for J/ψ decays produced in $\psi(2S) \to \pi^+\pi^- J/\psi$. Left: Signal MC for nine decay modes, right: data distribution obtained from the sideband-subtracted inclusive $\pi^+\pi^-$ samples (solid circles) and the fit to MC samples of different multiplicities (solid line).